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DYNAMICAL CLIMATOLOGY: A NEW APPROACH TO COMPUTING STATISTICAL-DYNAMICAL CLIMATOLOGIES

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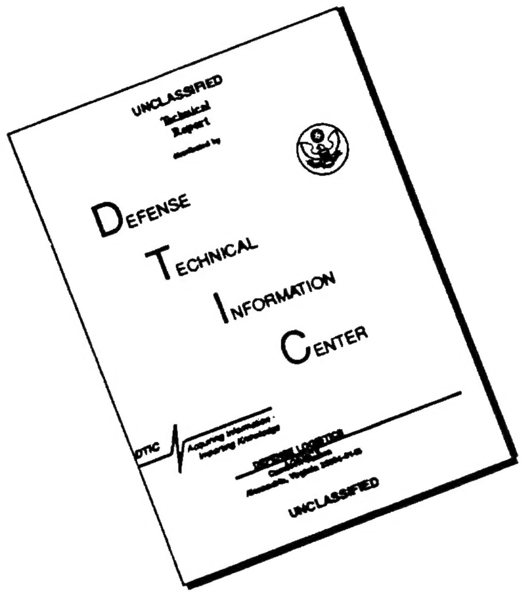

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James H. Corbin[1] and Ranjit Passi[2]

[1]Director, Mississippi State University Center for Air Sea Technology, Stennis Space Center, MS 39529-6000

[2]Consultant, Mississippi State University Center for Air Sea Technology, Stennis Space Center, MS 39529-6000

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ABSTRACT

To alleviate the problem of ever-shrinking resources, the military must take advantage of the advances in computer technology in the areas of databases and database management systems, graphics and visualization, and analytic tools. When properly integrated, these tools and advances will obviate the necessity of on-scene exercises that may be necessary for advance strategic planning, personnel training, and equipment design and testing. Real-time observations of the environmental factors affecting theater warfare scenarios can be successfully simulated from 'smart' climatologies that are based on the above state-of-the-art computer technologies and analysis tools. This concept paper gives a brief description of the efforts of the Mississippi State University (MSU) Center for Air Sea Technology (CAST) on establishing consistent environmental climatological data bases. A novel approach has been developed that employs a dynamical model of the ocean and statistical methodology (optimum interpolation) for combining the model output with historical observations to derive statistical-dynamical climatologies. In addition, the statistical climatologies can be supplemented with brief histories of relevant events that can be used for edificational purposes.

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1. INTRODUCTION

In the theater warfare simulation applications, and in the real-time deployment of personnel and the weapon/sensor systems, there is an urgent need for statistical climatologies of the ocean and atmosphere. The success of the mission depends upon anticipating the environmental conditions at the scene. Since there is often a lack and/or sparsity of real time observations, one can take advantage of statistical climatologies to build a probabilistic forecast model of the expected environmental elements. At a minimum, the space-time variability can be accounted for by including percentiles of the distributions of the environmental variables. With some additional effort and ingenuity, these climatologies can be made smart enough to provide 'what if' space-time scenarios in terms of conditional statistical distributions; and, if possible, include actual history of certain pertinent events.

A critical factor in modeling and simulations for military applications is the ability to produce a realistic natural environment. To date, most simulations have at best incorporated only simple climatological data. As the budget problems increase there will be an even greater demand for computer simulations of all aspects of military applications, from training scenarios and sensor/system design evaluation to strategic and tactical planning for probability of success estimates. Personnel and equipment safety will be paramount considerations, so it is imperative for the natural environmental estimates/simulations to be as realistic as possible. For advance planning, training, and equipment design considerations, real time data is not feasible, nor even desired. Climatologies will play a key role. But current climatological estimates are usually highly smoothed out and represent only the mean conditions in both time and space. Even when information on the extremes is available, it is usually limited in time and space. And if a system could be developed for collecting observational data at greater resolutions, it would be cost prohibitive, as well as time consuming. One solution is to use available historical and current observations of the natural environment assimilated into a dynamical numerical model. The result is a physically consistent data set field that can be produced at any reasonable resolution in both time and space, to match the requirements of the military application or warfare simulation.

This paper provides a brief description of the Mississippi State University (MSU) Center for Air Sea Technology (CAST) work on computing statistical-dynamical climatologies using a novel approach that employs a dynamical model of the ocean and statistical methodology (optimum interpolation) for combining the model output with historical observations. We recognize that such a combination of dynamical model and statistical methodology may not be either applicable or available for all situations. In such cases, optimal statistical data fusion methodologies can be used to derive appropriate climatologies of the environment.

2. A NEW APPROACH

A novel approach is presented here to derive dynamically adjusted seasonal climatology which was used to estimate the climatology of the Gulf of Mexico, as shown in Figures 1, 2 and 3. The resultant climatology is consistent with mass and momentum conservation principles. This constraint is important if the climatology is to be used in model simulations, and the model is to be spun up in a short time. Due to data sparsity and inaccuracies, climatological means of environmental parameters derived without dynamical constraints from archived historical data may yield fields which are inconsistent with the actual atmospheric forcing and topography/bathymetry.

To help overcome this limitation, we used a statistical-dynamical approach which employed a primitive equation numerical ocean circulation model in conjunction with a four-dimensional data assimilation scheme to produce dynamically interpolated climatology. The general strategy was to initialize the model with climatological mean (temperature and salinity fields in case of the ocean modeling), and run the model through several annual cycles of external forcing, assimilating daily climatological data until the assimilation process stabilized, and retaining the results for the last year as the dynamical climatology. The stability of the process is determined from the successive computed values of the pattern correlation and the root mean square differences between year-apart fields. The stability of the integration process is established when: the coefficient pattern correlation, starting from a small magnitude stabilizes with a small fluctuation around a maximum value (close to one); and the root mean square, starting with a relatively large value, decreases to a minimmum value, and then fluctuates around it from there on. The two stabilizations (pattern correlation and root mean square difference) seem to happen around the same time. This strategy provided a means for combining a dynamical model and historical data in an attempt to arrive at more consistent and higher resolution climatological fields.

The quality of the dynamical climatology so obtained depends on three components, namely, the hydrodynamic/atmospheric model, the data assimilation scheme employed, and the historical data set to be assimilated. The hydrodynamic model should possess the requisite physics of the region, and be validated to reproduce the dynamic features of the region when the model is forced with real time forcings. The data assimilation scheme should incorporate the prevailing correlation length scales and be able to assimilate all possible data types. While there is no control on the quantity and quality of the data, the data should be adequate to constrain the model in space and time. The data sets should be quality controlled to a large extent.

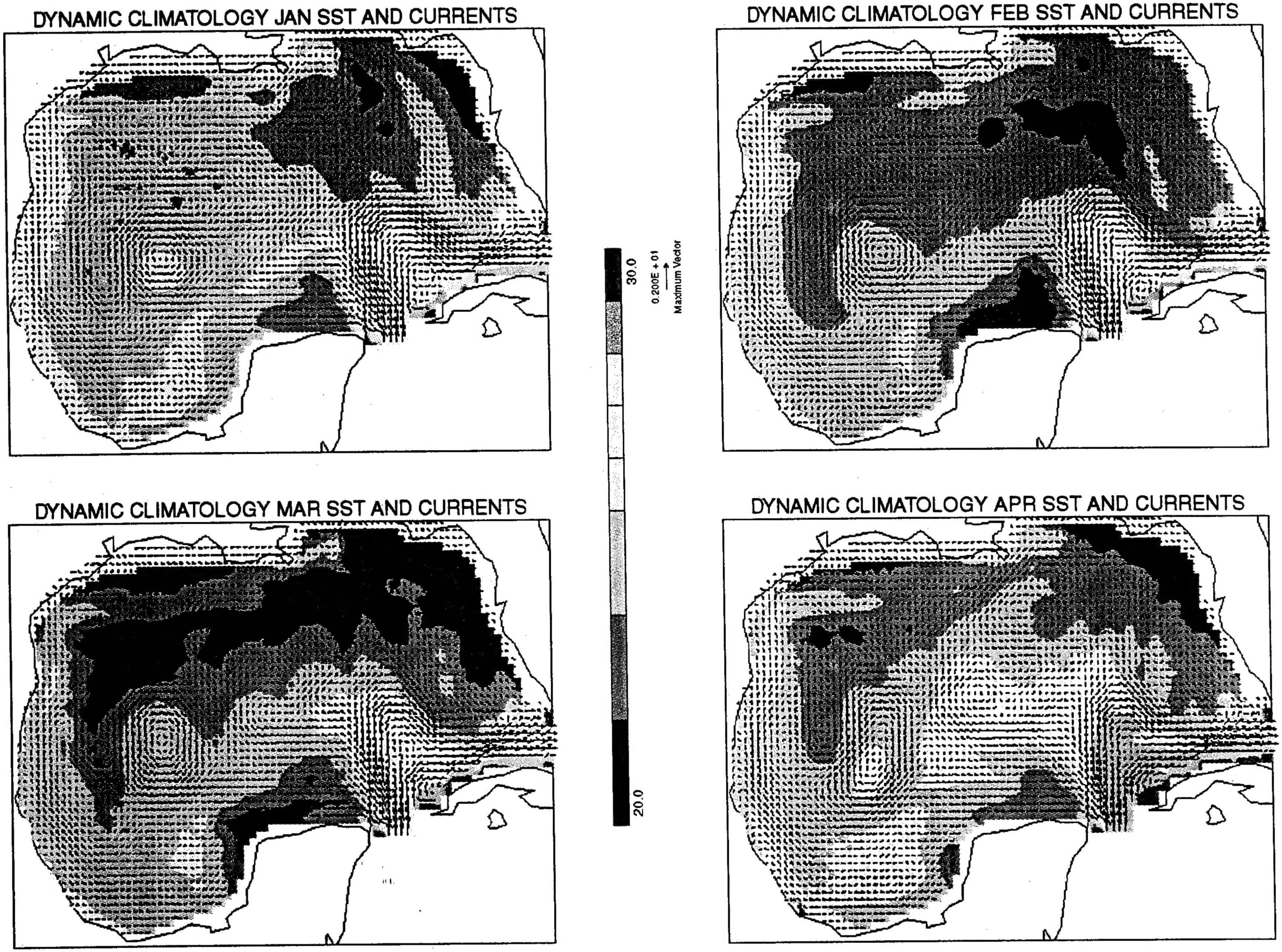

Fig. 1 A monthly dynamical climatology of the Gulf of Mexico derived using the Princeton Ocean Model assimilating temperature/salinity casts from Levitus(1982)

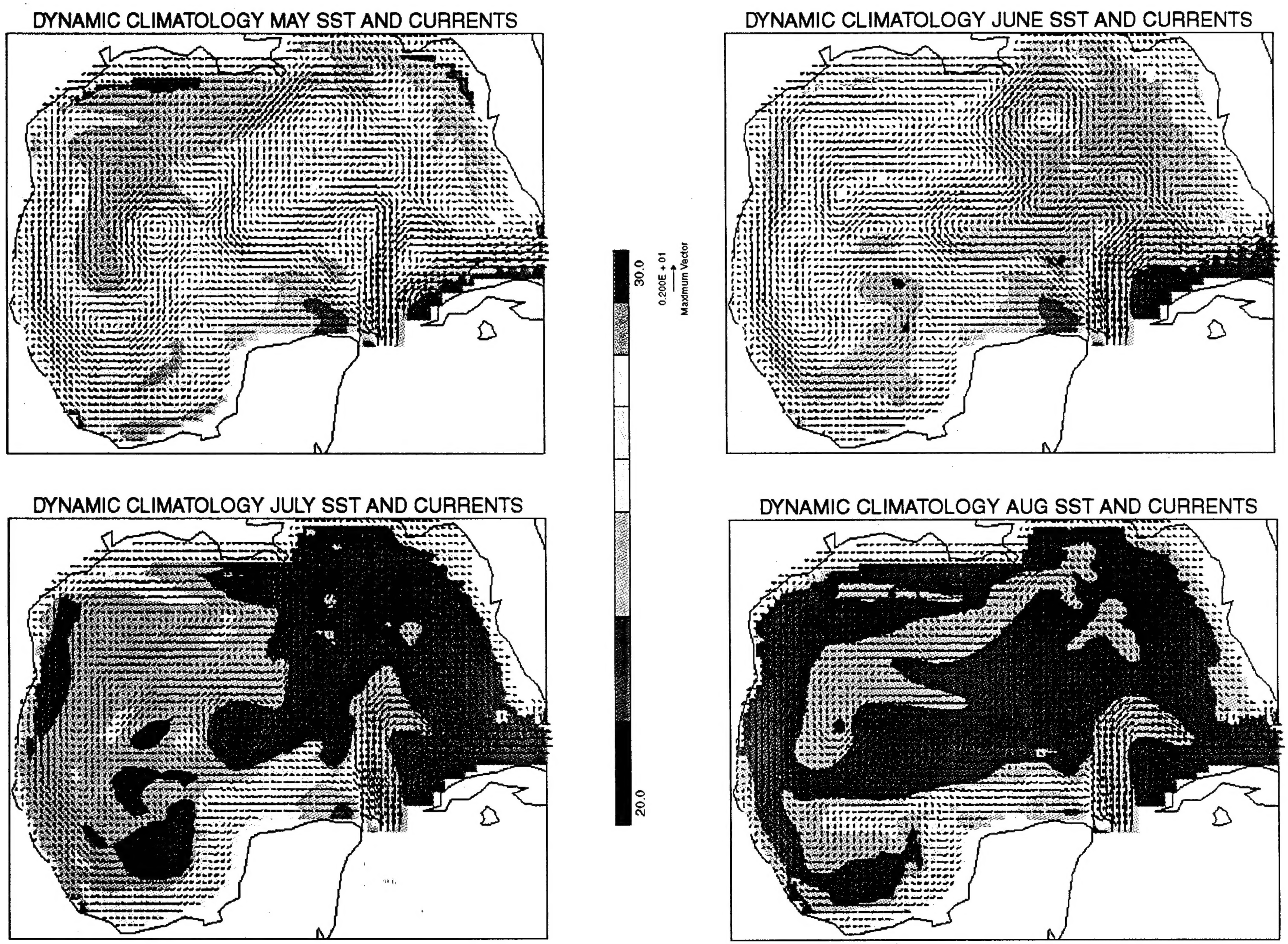

Fig. 2 A monthly dynamical climatology of the Gulf of Mexico derived using the Princeton Ocean Model assimilating temperature/salinity casts from Levitus(1982)

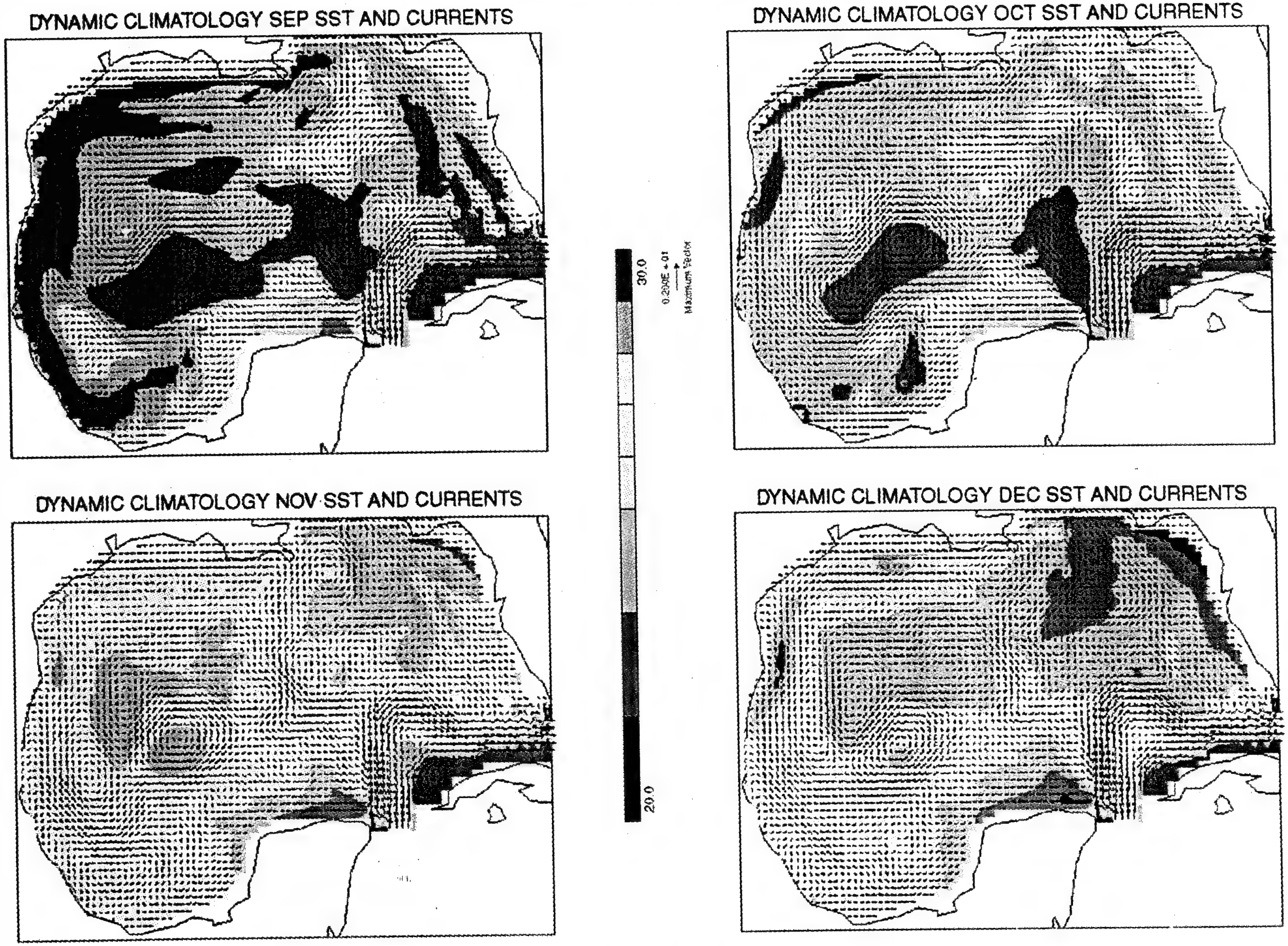

Fig. 3 A monthly dynamical climatology of the Gulf of Mexico derived using the Princeton Ocean Model assimilating temperature/salinity casts from Levitus(1982)

3. STATISTICAL FORMULATION OF THE DATA ASSIMILATION PROBLEM

The purpose of data assimilation is to estimate the true state of the ocean, Θ, by combining the model output, $\mathbf{T}_m$, and observations $\mathbf{T}_o$. The combined estimator (after dynamic initialization, in some cases; see Daley, 1991) is then used as the initial condition for the model integration. The vectors Θ and $\mathbf{T}_m$ are N-vectors defined on the model grid, $\mathcal{G}_m$; the observation vector, $\mathbf{T}_o$, is an M-vector defined on the observation grid $\mathcal{G}_o$.

Usually, $M \ll N$, and $\mathbf{T}_o$ alone cannot provide an adequate representation of Θ. Thus, assimilation is performed resulting in initial conditions on $\mathcal{G}_m$, which are used for the numerical integration of the model equations. We assume there exists a mapping such that $\mathbf{D}(\mathcal{G}_m) = \mathcal{G}_o$. Then Θ_o, the true state of the ocean at the observation grid, can be written as $\Theta_o = \mathbf{D}(\Theta)$. Often $\mathbf{D}$ is assumed to be a linear mapping so that:

$$\Theta_o = \mathbf{D}\Theta. \tag{1}$$

The motivation to perform such data assimilation is the assumption that both the model values and the observational data are unbiased estimators of the true state of the ocean, so that the optimal combination of the two will lead to an estimator of Θ, which has a smaller error variance than either of the two. Under the unbiasedness assumption, we can write the following linear model:

$$\begin{pmatrix} \mathbf{T}_m \\ \mathbf{T}_0 \end{pmatrix} = \begin{pmatrix} \Theta \\ \mathbf{D}\Theta \end{pmatrix} + \begin{pmatrix} \mathbf{e}_m \\ \mathbf{e}_0 \end{pmatrix} \tag{2}$$

where $\mathbf{e}_m$ and $\mathbf{e}_o$ are vectors of zero mean, random errors in the model output and observations, with Σ_m and Σ_o as their respective covariance matrices. It is reasonable to assume that the errors in $\mathbf{T}_o$ and $\mathbf{T}_m$ are statistically independent. Then the least squares solution to the true state Θ is obtained by minimizing the quadratic functional:

$$\mathcal{Q} = (\mathbf{T}_m - \Theta)'\Sigma_m^{-1}(\mathbf{T}_m - \Theta) + (\mathbf{T}_o - \mathbf{D}\Theta)'\Sigma_o^{-1}(\mathbf{T}_o - \mathbf{D}\Theta) \tag{3}$$

where the prime indicates matrix transposition. It is customary to write $\mathcal{Q}$ in terms of corrections to the model values:

$$\mathcal{Q} = \mathbf{T}_c'\Sigma_m^{-1}\mathbf{T}_c + (\mathbf{D}\mathbf{T}_c - \mathbf{T}_{co})'\Sigma_o^{-1}(\mathbf{D}\mathbf{T}_c - \mathbf{T}_{co}), \tag{4}$$

where $\mathbf{T}_c = \mathbf{T}_m - \Theta$ and $\mathbf{T}_{co} = \mathbf{D}\mathbf{T}_m - \mathbf{T}_o$. Ordinarily, this minimization should be quite simple but for the large dimensions of the model grid, and hence that of the covariance matrix, Σ_m; thus, the routinely used optimization procedures are inadequate, and more efficient minimization algorithms must be devised (Derber and Rosati, 1989; Passi et al., 1996).

4. AN APPLICATION: A DYNAMIC CLIMATOLOGY OF THE GULF OF MEXICO

The feasibility of the approach has been shown in deriving a dynamic climatology of the Gulf of Mexico. The primitive equation model employed was the Princeton Ocean Model which was combined with a four-dimensional data assimilation scheme (Derber and Rosati, 1989; Passi et al., 1996).

The model was run through two annual cycles of external forcing, assimilating daily observations from a climatological data base consisting of temperature and salinity casts that were the basis of the Levitus analysis (Levitus, 1982). Based on the pattern correlation and the root mean square computations between a year-apart field values, the assimilation process was seen to have stabilized after a two year integration. The resulting daily temperature, salinity, sea surface height and velocity fields for the last year were time-averaged to provide a dynamically-adjusted climatology with seasonal resolution. The resulting dynamic climatology reproduced several realistic features of the Gulf, including the seasonal variation of the surface temperature and the dynamic features of the protruding and contracting Loop Current. See Figures 1, 2 and 3 for details.

5. CONCEPT OF A LIVING ATLAS

Although the dynamical climatology concept provides us with a consistent data set, the data lack the dynamic component, i.e., it is static and there is no three-dimensional motion in time associated with the feature. However, it may be desirable to store in the database some typical features that are representative of the percentiles of the statistical distribution. In another study funded by the Office of Naval Research (ONR), CAST is developing a living atlas of both oceans and atmosphere. It may be desirable to include some of the elements of this approach in this effort. The concept of the living atlas is to derive and store only the pertinent information as 'metadata' in a modern database with a pointer back to the original source. The metadata is then coupled to a user and applications interface that allows the user to query and search the database and extract only the information of interest. The extracted information is displayed to the user in an appropriate form or directly passed to an application selected for further processing. Such a system could allow for interactive updating of the climatology or for selective extraction of space-time events for real time edification. For example, supposing an investigator needs information on hurricanes originating in the Caribbean, then a living atlas contains the metadata information on all relevant events of interest. Thus, the user could interactively access and extract the desired hurricane information as follows.

- Typical Hurricane: Provide the basic information on the wind speed (miles/per hour), low pressure (mbs), translation speed, the amount of damage ($) etc.
- Examples of Hurricanes of Specified Intensity: Extract from the database information on all hurricanes with a specified intensity; provide 3-D motions of the hurricanes from the IR imagery from the inception to the end.
- Atmospheric Conditions Before-and-After: Extract information from the database and provide visual graphics of the atmospheric model (NOGAPS/NORAPS) analyses from a few days before the hurricane inception to a few days after its demise.
- Hurricanes Coming Through Gulf of Mexico: Extract information on all hurricanes proceeding through the Gulf of Mexico, providing complete tracks and model analyses.

The characteristics of the project described above should be incorporated in the climatologies to be built, so that intelligent decisions can be made based upon past historical records.

6. CONCLUDING REMARKS

We have given a brief description of the MSU CAST efforts that could be utilized and enhanced for building statistical-dynamical climatologies of the environment of interest. CAST has the necessary expertise in database management, visualization, quality control and analysis to provide innovative concepts for building climatologies that can be used for the warfare scenarios. Further, we have begun forming a teaming relationship with other universities to bring in explicit expertise in the other related areas.

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DISTRIBUTION LIST

Scientific Officer Code 1242
Tom Curtin (3)
Office of Naval Research
800 North Quincy Street
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Office of Naval Research
800 North Quincy Street
Arlington, VA 22217-5000
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Dr. Steve Haeger
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Dr. Ted Bennett
Naval Oceanographic Office
Stennis Space Center, MS 39529

Dr. Lakshmi Kantha
University of Colorado
Colorado Center for Astrodynamics Research
Campus Box 431
Boulder, CO 80309-0431

Dr. James K. Lewis
Ocean Physics Research & Development
207 S. Seashore Drive
Long Beach, MS 39560

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